

Microlensing of Quasar Broad Emission Lines: Constraints on Broad Line Region Size

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ABSTRACT

We measure the differential microlensing of the broad emission lines between 18 quasar image pairs in 16 gravitational lenses. We find that high ionization lines such as CIV are more strongly microlensed than low ionization lines such as CIII] or H β , indicating that the high ionization line emission regions are more compact. If we statistically model the distribution of microlensing magnifications, we obtain estimates for the broad line region size of $r_s = 24_{-15}^{+22}$ and $r_s = 55_{-35}^{+150}$ light-days (90% confidence) for the high and low ionization lines, respectively. When the sample is divided attending to quasar luminosity, we find that the line emission regions of more luminous quasars are larger, with a slope consistent with the expected scaling from photoionization models. Our estimates also agree well with the results from local reverberation mapping studies.

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1. Introduction

Strong, broad emission lines are characteristic of many active galactic nuclei (AGN), and their physical origins are important by virtue of their proximity to the central engine and their potential use as probes of the gas flows either fueling the AGN or feeding mass and energy back into the host galaxy. To date, the primary probe of the geometry and kinematics of the broad line regions has been reverberation mapping, where the delayed response of the emission line flux to changes in the photoionizing continuum is used to estimate the distance of the line emitting material from the central engine (see, e.g., the reviews by Peterson 1993, 2006). Reverberation mapping studies have shown that the global structure of the broad line region is consistent with photoionization models, with the radius increasing with the (roughly) square root of the continuum luminosity (e.g. Bentz et al. 2009) and high ionization lines (e.g. CIV) originating at smaller radii than low ionization lines (e.g. $H\beta$). Recent studies have increasingly focused on measuring the delays as a function of line velocity in order to understand the kinematics of the broad line region (Denney et al. 2009, 2010, Bentz et al. 2010, Brewer et al. 2011, Doroshenko et al. 2012, Pancoast et al. 2012). The results to date suggest that there is no common kinematic structure, with differing sources showing signs of inward, outward and disk-like velocity structures.

While very successful, reverberation mapping suffers from several limitations. First, the studies are largely limited to relatively nearby, lower luminosity AGN because the delay time scales for distant, luminous quasars are longer than existing monitoring programs can be sustained. Not only do the higher luminosities increase the intrinsic length of the delay (which is then further lengthened by the cosmological redshift), but the higher luminosity quasars also have lower variability amplitudes (see, e.g., MacLeod et al. 2010). Second, one of the most important applications of the results of reverberation mapping at present is as a calibrator for estimating black hole masses from single epoch spectra (Wandel et al. 1999). These calibrations are virtually all for the $H\alpha$ and $H\beta$ lines, while the easiest lines to measure for high redshift quasars are the MgII and CIV lines because the Balmer lines now lie in the infrared. Without direct calibrations, there is a contentious debate about the reliability of MgII (e.g., McLure & Jarvis (2002), Kollmeier et al. (2006), Shen et al. (2008), Onken & Kollmeier (2008)) and CIV (e.g., Vestergaard & Peterson (2006), Netzer et al. (2007), Fine et al. (2010), Assef et al. (2011)) black hole mass estimates.

An alternative means of studying the structure of the broad line region is to examine how it is microlensed in gravitationally lensed quasars. In microlensing, the stars in the lens galaxy differentially magnify components of the quasar emission regions leading to time and wavelength dependent changes in the flux ratios of the images (see the review by Wambsganss 2006). The amplitude of the magnification is controlled by the size of the emission

region, with smaller source regions showing larger magnifications. The broad line region was initially considered to be too large to be affected by microlensing (Nemiroff 1988, Schneider & Wambsganss 1990), but for sizes consistent with the reverberation mapping results the broad line regions should show microlensing variability (see Mosquera & Kochanek 2011) as explored in theoretical studies by Abajas et al. (2002, 2007), Lewis & Iбата (2004) and Garsden et al (2011). Observational evidence for microlensing in the broad line region has been discussed for Q2237+0305 (Lewis et al. 1998, Metcalf et al. 2004, Wayth et al. 2005, Eigenbrod et al. 2008, O’Dowd et al. 2010, Sluse et al. 2011), SDSS J1004+4112 (Richards et al. 2004, Gómez-Álvarez et al. 2006, Lamer et al. 2006, Abajas et al. 2007) and SDSS J0924+0219 (Keeton et al. 2006), as well as in broader surveys by Sluse et al. (2012) and Motta et al. (2012). For example, in their detailed study of Q2237+0305, Sluse et al. (2011) demonstrated the power of microlensing, obtaining estimates of the BLR size for both CIII] ($r_{CIII]} \sim 49$ light-days) and CIV ($r_{CIV} \sim 66$ light-days) emission lines. Like reverberation mapping, the microlensing size estimates can also be made as a function of velocity, and the two methods can even be combined to provide even more detailed constraints (see Garsden et al. 2011).

Here we survey microlensing of the broad emission lines in a sample of 19 pairs of lensed quasar images compiled by Mediavilla et al. (2009). In §2 we describe the data and show that the line core and higher velocity wings are differentially microlensed. In §3 we use these differences to derive constraints on the size of the line emitting regions and we summarize the results in §4.

2. Data Analysis

In Mediavilla et al. (2009) we collected (from the literature) the UV, optical and near-IR spectra shown in Figures 1 and 2 and summarized in Table 1. After excluding some of the noisier spectra used in Mediavilla et al. (2009), we are left with a sample of 18 pairs of lensed quasar images. If we examine the low ionization lines (CIII] λ 1909, MgII λ 2798, H β λ 4861 and H α λ 6562) there is generally a very good match in the emission line profiles between images. For the high ionization lines¹ (OVI] λ 1035, Ly α +NV λ 1216, SiIV+OIV λ 1400 and CIV λ 1549), there are five examples where there are obvious differences in the line profiles: CIV in HE0435–1223DC, Ly α +NV in SBS0909+532, and Ly α +NV, SiIV+OIV] and CIV] in SDSS J1004+4112BA). SDSS J1004+4112 is a well-known example (Richards et al. 2004,

¹We have included Ly α +NV in the high ionization group, since it is observed to have a similar reverberation lag to CIV (Clavel et al. 1991).

Gómez-Álvarez et al. 2006, Lamer et al. 2006, Abajas et al. 2007, Motta et al. 2012), where a blue bump appears in several high ionization emission lines, as illustrated by the more detailed view of the SiIV λ 1400 line in Figure 3.

In order to quantify the effects of microlensing on the broad line region, we want to isolate the effects of microlensing from those due to the large scale macro magnification, millilensing (e.g. Dalal & Kochanek 2002) and extinction (e.g. Motta et al. 2002). We attempt this by looking at differential flux ratios between the cores and wings of the emission lines observed in two images

$$\Delta m = (m_1 - m_2)_{wings} - (m_1 - m_2)_{core}. \quad (1)$$

These magnitudes are constructed from the line fluxes found after subtracting a linear model for the continuum emission underneath the line profile. Since the line emission regions are relatively compact and the wavelength differences are small, this estimator certainly removes the effects of the macro magnification, millilensing and extinction.

We are going to assume that the line core, defined by the velocity range $|\Delta v| < 850$ km/s, is little affected by microlensing compared to the wings. Existing velocity-resolved reverberation maps (Denney et al. 2009, 2010, Bentz et al. 2010, Barth et al. 2011, Pancoast et al. 2012) all find longer time delays in this velocity range, indicating that the material in the line core generally lies at larger distances from the central engine. Sluse et al. (2011) also found this in their microlensing analysis of Q2237+0305. Essentially, high velocity material must be close to the central engine to have the observed Doppler shifts, while the low velocity material is a mixture of material close to the black hole but moving perpendicular to the line of sight and material far from the black hole with intrinsically low velocities. As a result, the line core should generically be produced by material spread over a broader area and hence be significantly less microlensed than the line wings.

Figure 4 shows histograms of Δm for the low and high ionization lines, and the values are reported in Table 1. The first point to note is that even the largest microlensing effects are relatively small, with $|\Delta m| < 0.2$ mag. The second point to note is that more high ionization lines (6 of 14) than low ionization lines (2 of 14) show significantly non-zero Δm given the typical uncertainties (0.05 mag). Here we are counting only image pairs showing the anomalies, not the numbers of lines showing anomalies, so a system like SDSSJ 1004+4112 with multiple high ionization anomalies is counted only once. Qualitatively, it is clear that both high and low ionization lines are weakly microlensed and that the low ionization lines arise from a larger source than the high ionization lines.

3. Constraining the Size of the Broad Line Region

Given these estimates of the differential effects of microlensing on the core and wings of the emission lines, we can use standard microlensing Monte Carlo methods to estimate the size of the emission regions. For simplicity in a first calculation we assume that the line core emission regions are large enough that they are effectively not microlensed, and simply model the wing emission regions as Gaussians. Mortonson et al. (2005) have shown that the effects of microlensing are largely controlled by the projected half-light area of the source, and even with full microlensing light curves it is difficult to estimate the shape of the emission regions (see Poindexter & Kochanek (2010), Blackburne et al. (2011)).

We use the estimates of the dimensionless surface density κ and shear γ of the lens for each image from Mediavilla et al. (2009) or the updated values for SBS 0909+532 from Mediavilla et al. (2011a). We assume that the fraction of the mass in stars is 5%. For a stellar mass of $M = 1M_{\odot}$, we generated square magnification patterns for each image which were 1000 light-days across and had a 0.5 light-day pixel scale using the Inverse Polygon Mapping algorithm (Mediavilla et al. 2006, 2011b). The magnifications experienced by a Gaussian source of size r_s ($I \propto \exp(-R^2/2r_s^2)$) are then found by convolving the magnification pattern with the Gaussian. We used a logarithmic grid of source sizes, $\ln r_s = 0.3 \times i$ for $i = 0, \dots, 17$, where r_s is in units of light-days. The source sizes can be scaled to a different mean stellar mass as $r_s \propto (M/M_{\odot})^{1/2}$. We will follow a procedure similar to that used by Jiménez-Vicente et al. (2012) to estimate the average size of quasar accretion disks.

For any pair of images, we can generate the expected magnitude differences for a given source size by randomly drawing magnifications m_1 and m_2 from the convolved magnification pattern for the two images and taking the difference $\Delta m = m_1 - m_2$. The probability of observing a magnitude difference $\Delta m_{obs,k} \pm \sigma_k$ for lens/line k given a source size r_s is then

$$p_k(r_s) \propto \sum_{l=1}^N \exp \left(-\frac{1}{2} \left(\frac{\Delta m_l - \Delta m_{obs,k}}{\sigma_k} \right)^2 \right) \quad (2)$$

for $N = 10^8$ random trials at each source size. We can then estimate an average size for either the high or low ionization lines by combining the likelihoods

$$L(r_s) = \prod p_k(r_s) \quad (3)$$

for the individual lines. Implicitly we are also drawing magnifications for the core but assuming they are close enough to unity to be ignored.

Figure 5 shows the resulting likelihood functions for the high and low ionization lines. Simply using maximum likelihood estimation, we find 90% confidence estimates for the average sizes of the high and low ionization lines of $r_s = 24_{-15}^{+22}$ and $r_s = 55_{-35}^{+150}$ light-days,

respectively. We can make a rough estimate of the consequences of ignoring microlensing of the line core by raising (lowering) the magnifications to represent anti-correlated (correlated) changes in the core relative to the line. The effects of uncorrelated changes will be intermediate to these limits. For a 20% amplitude, the central sizes shift over the range from $r_s = 20$ to 37 light-days for the high ionization lines and $r_s = 37$ to 120 light-days for the low ionization lines.

The problem with more complex models is that there is no simple, generally accepted structural model for the broad line region, and the initial results of the velocity-resolved reverberation mapping experiments suggest that there may be no such common structure. As an experiment, we constructed a model consisting of an inner rotating disk and an outer spherical shell which dominates the core emission. We set the inner edge of the disk to $r_{disk,in} = 5$ light-days and left the outer edge $r_{disk,out}$ as the adjustable parameter. For simplicity we used a constant emissivity for the disk and a Keplerian rotation profile with an inner edge velocity of 10^4 km/s. The disk has an inclination of 45 degrees. For the spherical shell we adopted fixed inner and outer radii of $r_{sphere,in} = 60$ and $r_{sphere,out} = 160$ light-days respectively. For the shell we used a $v \propto 1/r^2$ velocity profile with a velocity of 5000 km/s at the inner edge. We normalized the models so that the disk contributes 20% of the flux at zero velocity, which also results in a single peaked line profile that resembles typical broad line profiles. We only carried out the calculations for a representative set of lens parameters ($\kappa_1 = \gamma_1 = 0.45$ and $\kappa_2 = \gamma_2 = 0.55$; see Mediavilla et al. 2009), but we now calculate Δm to correctly include the differential microlensing of the core and the wing. The final results for the outer radius of the disk component which dominates the wings of the line profile are $r_s = 50^{+40}_{-20}$ and $r_s = 70 \pm 30$ light-days the high and low ionization lines, respectively, where these are now 1σ uncertainties. While the model is somewhat arbitrary, the similarity of the results to the simpler analysis suggest that it was relatively safe to ignore the complexities.

4. Conclusions

Consistent with other recent studies (e.g. Sluse et al. 2011, 2012, Motta et al. 2012) we have found that the broad emission lines of gravitationally lensed quasars are weakly microlensed. We also find for the first time that high and low ionization lines appear to be microlensed differently, with higher magnifications observed for the higher ionization lines. This indicates that the emission regions associated with the high ionization lines are more compact, as would be expected from photoionization models. If we then make simple models of the microlensing effects, we obtain size estimates of $r_s = 24^{+22}_{-15} \sqrt{M/M_\odot}$ and $r_s = 55^{+150}_{-35} \sqrt{M/M_\odot}$ light-days for the high and low ionization lines. We also calculated the sizes

for low ($L < 2 \times 10^{44}$ ergs s $^{-1}$) and high ($L > 2 \times 10^{44}$ ergs s $^{-1}$) luminosity sub-samples based on the magnification-corrected luminosity estimates from Mosquera & Kochanek (2011). For the low luminosity sub-sample we find $r_s = 16_{-8}^{+11} \sqrt{M/M_\odot}$ and $37_{-18}^{+28} \sqrt{M/M_\odot}$ light-days for the high and low ionization lines, while for the high luminosity sub-sample we find $r_s = 36_{-14}^{+30} \sqrt{M/M_\odot}$ and $r_s = 299_{-103}^{+indet.} \sqrt{M/M_\odot}$ light-days. While the uncertainties are too large to accurately estimate the scaling of the size with luminosity, the changes are consistent with the $L^{1/2}$ scaling expected from simple photoionization models.

Figure 6 compares these estimates to the results from the reverberation mapping of local AGN using the uniform lag estimates by Zu et al. (2011) and the host galaxy-corrected luminosities of Bentz et al. (2009). In this figure we have scaled our estimates of r_s for microlenses of $M = 0.3M_\odot$. While the uncertainties in our microlensing estimates are relatively large, the agreement with the reverberation mapping results is striking. This is clearest for the low ionization lines which are the ones easily measured in ground-based reverberation mapping campaigns, but the offset we find between the high and low ionization lines agrees with the offsets seen for the limited number of reverberation mapping results for high ionization lines. We also show the estimated size of the CIV emission region for Q2237+030 by Sluse et al. (2011) which shows a similar level of agreement. Because we are measuring the size of the higher velocity line components rather than the full line, our results should be somewhat smaller than the reverberation mapping estimates for the full line. These results strongly suggest that the lensed quasars can provide an independent check of reverberation mapping results and extend them to far more distant quasars relatively economically. Microlensing should also be able to address the controversies about lines like CIV which have few direct reverberation mapping measurements but are crucial tools for studying the evolution of black holes at higher redshifts.

With nearly 100 lensed quasars (see Mosquera & Kochanek (2011)) it is relatively easy to expand the sample and to begin making estimates of the size as a function of luminosity or other variables. Accurate estimates for individual quasars will probably require spectrophotometric monitoring, as done by Sluse et al. (2011). Since the broad line emission regions are relatively large, the time scale for the variability is relatively long. A significant constraint can be gained for most of these lenses simply by obtaining one additional spectrum to search for changes over the years that have elapsed since many of the archival spectra we have used here were taken. The lenses may also be some of the better targets for reverberation studies at higher redshifts because the time delays of the images provide early warning of continuum flux changes and better temporal sampling of both the line and continuum for the same investment of observing resources.

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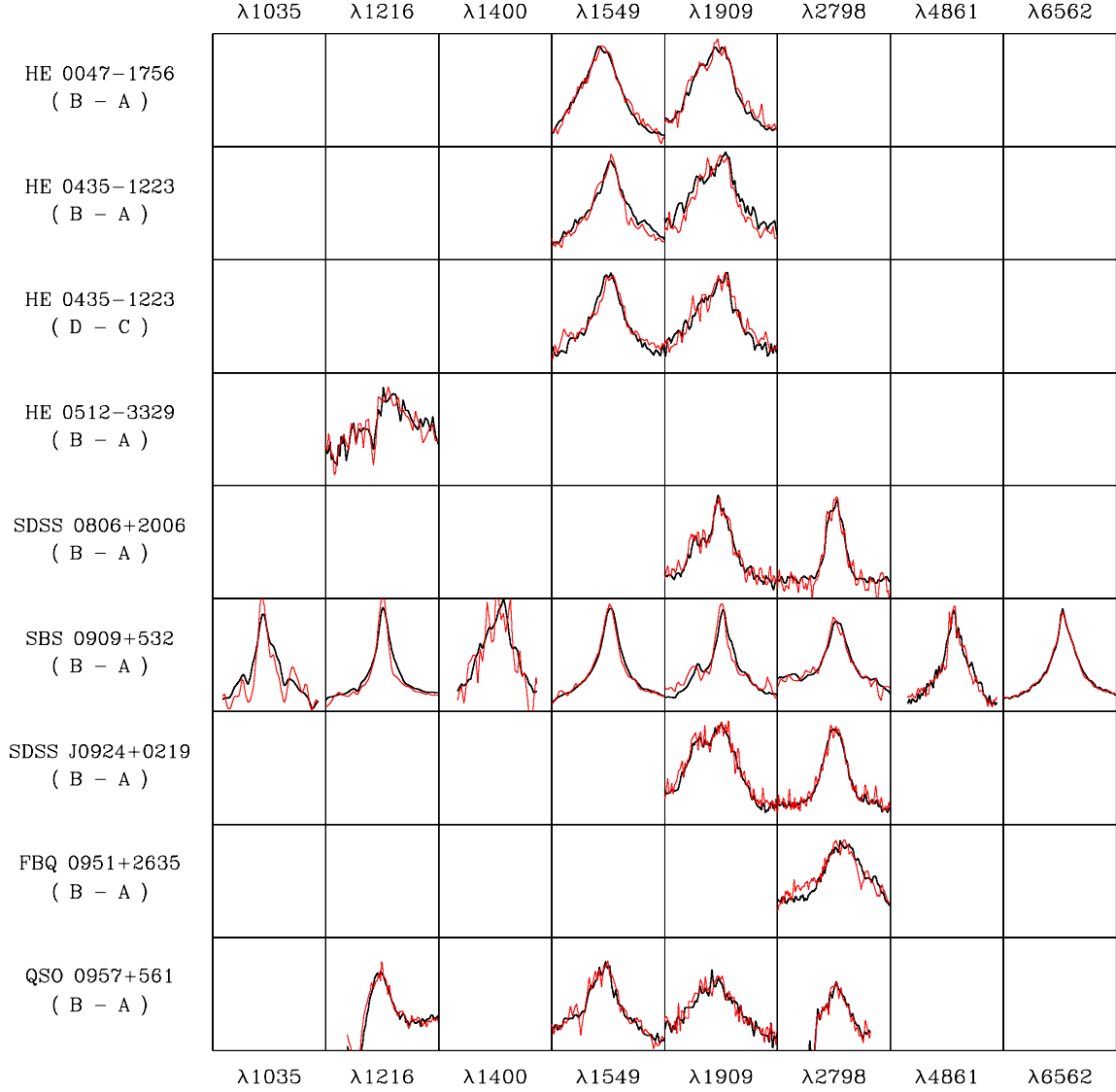


Fig. 1.— Panels showing superpositions of emission line profiles for image pairs of several lens systems (continue in Figure 2). Continuum subtracted spectra have been scaled to match the lines. Each emission line is plotted in the $(-6000 \text{ km s}^{-1}, 6000 \text{ km s}^{-1})$ range.

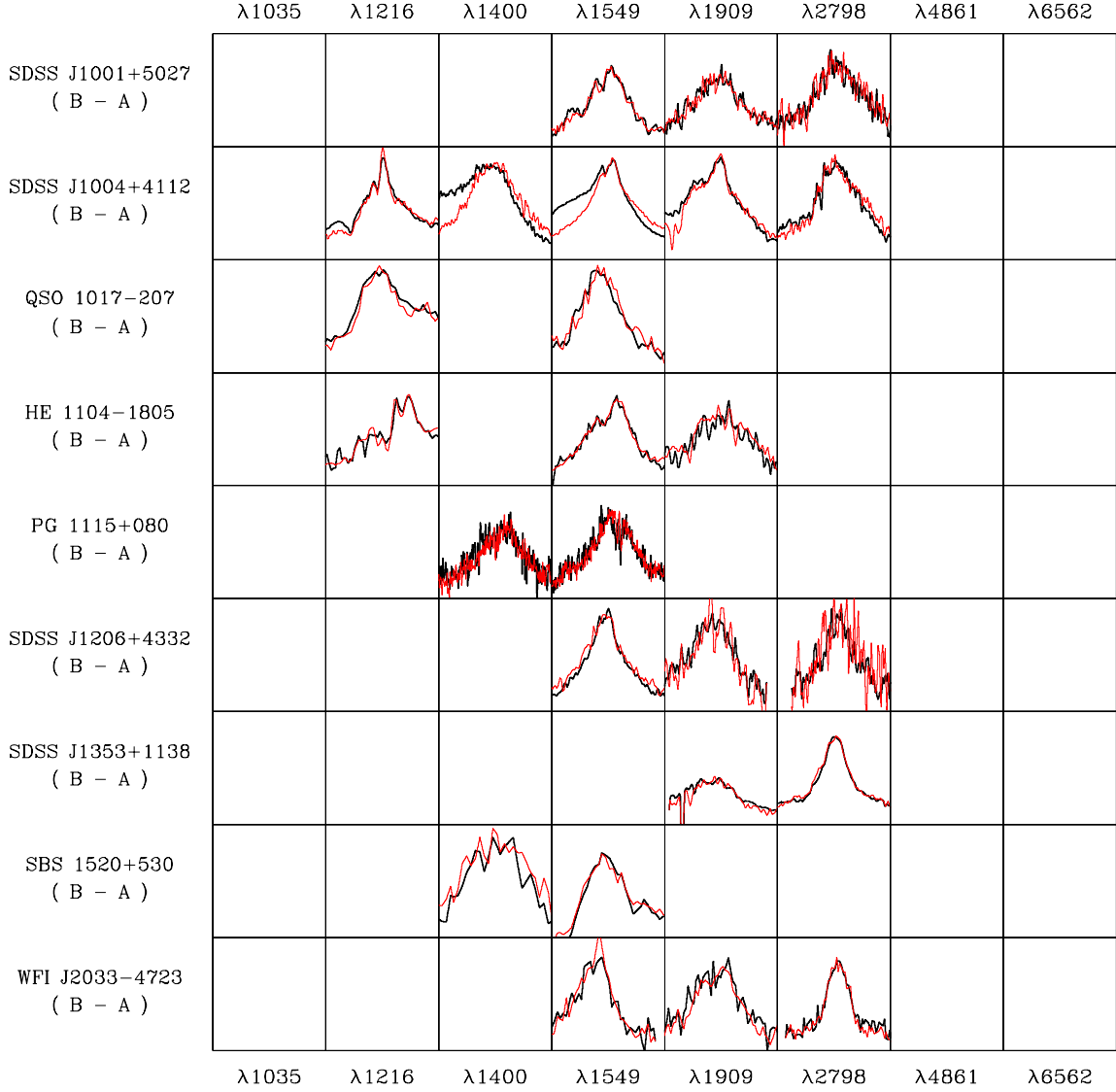


Fig. 2.— (continuation of Figure 1) Panels showing superpositions of emission line profiles for image pairs of several lens systems. Continuum subtracted spectra have been scaled to match the lines. Each emission line is plotted in the $(-6000 \text{ km s}^{-1}, 6000 \text{ km s}^{-1})$ range.

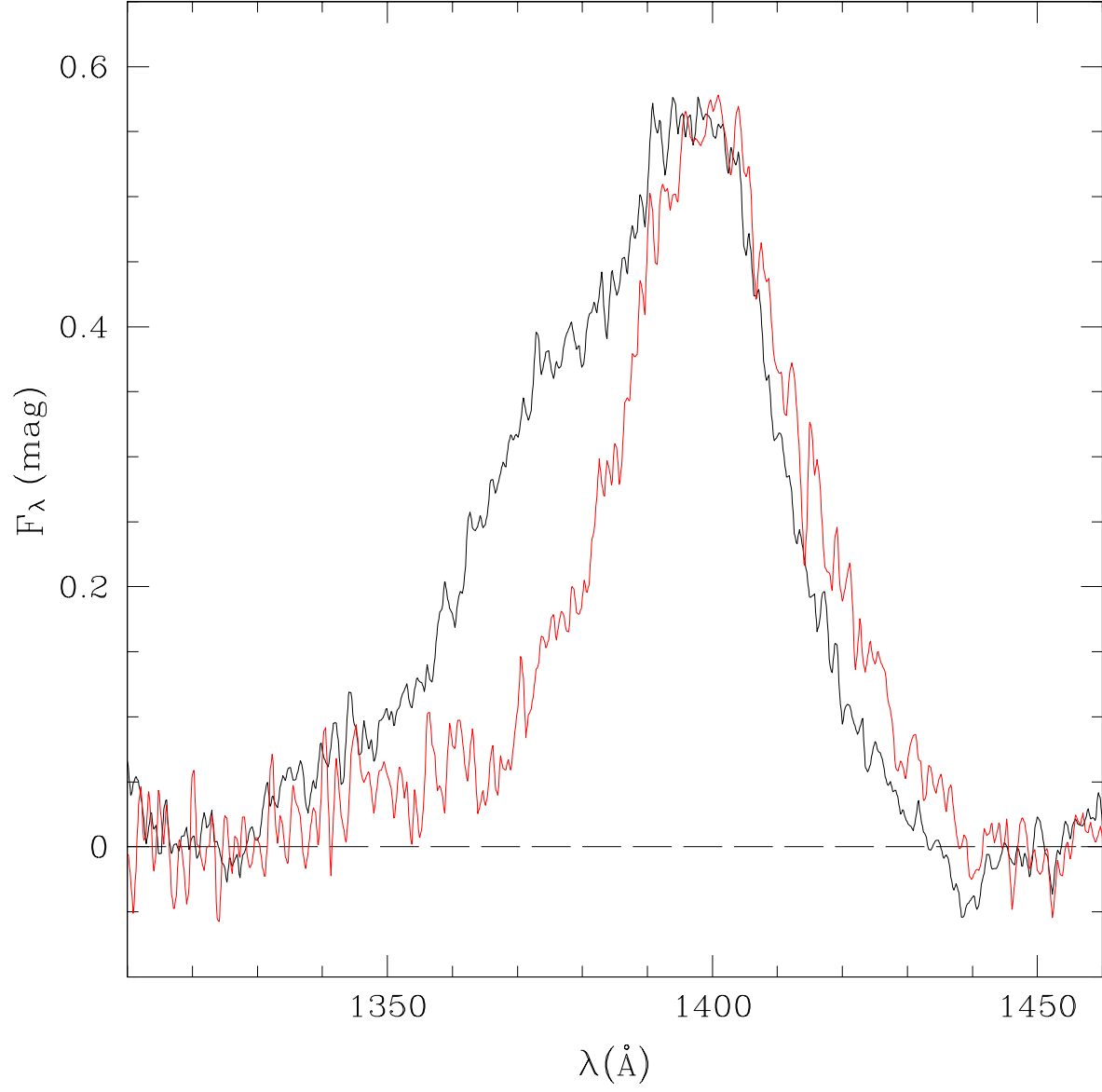


Fig. 3.— A detailed view of the differences in the SiIV λ 1400 line profiles corresponding to the A and B images of SDSS J1004+4112 from Richards et al. (2004).

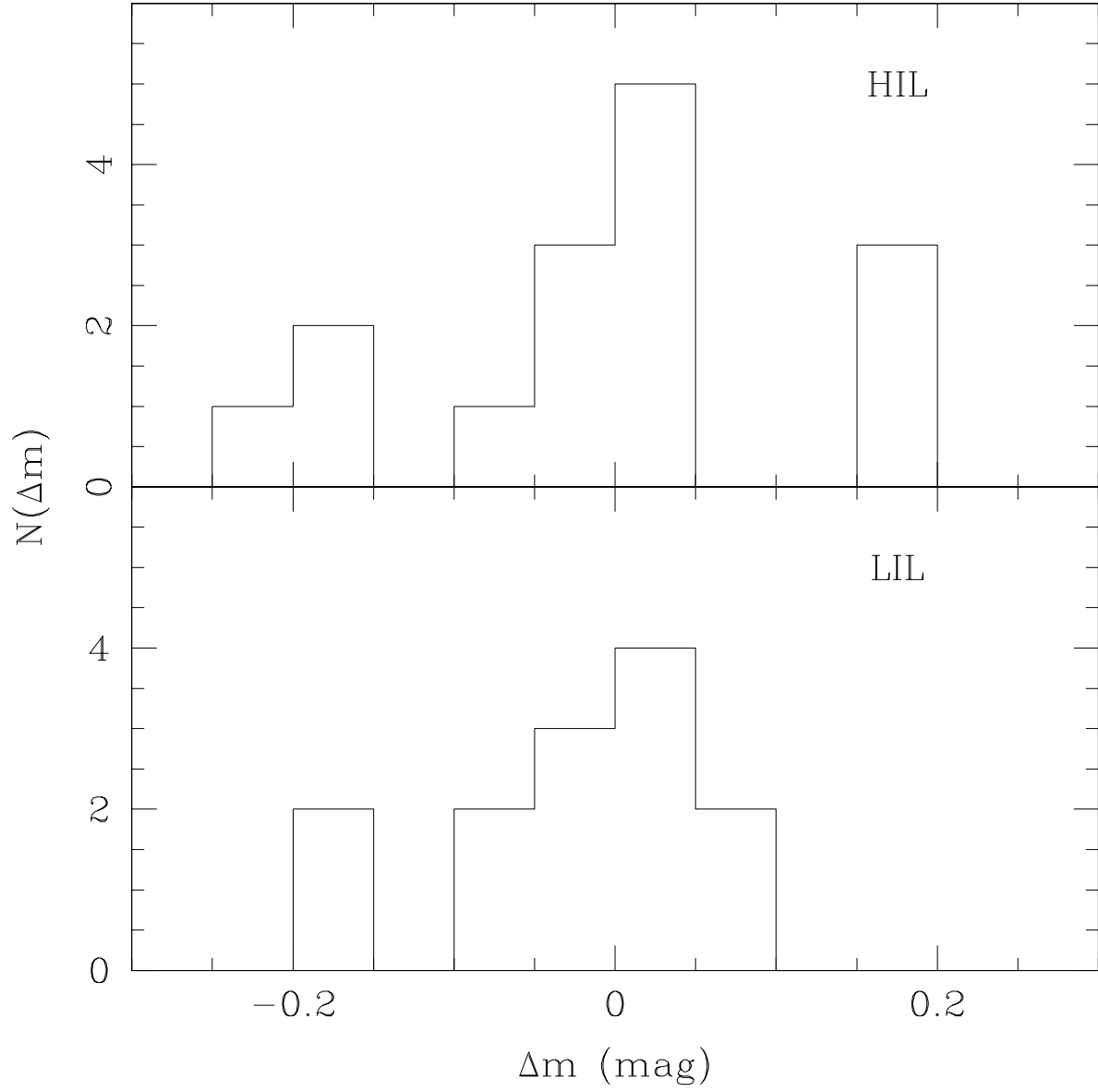


Fig. 4.— Histograms of the microlensing magnifications, Δm , observed for the high (upper) and low (lower) ionization lines.

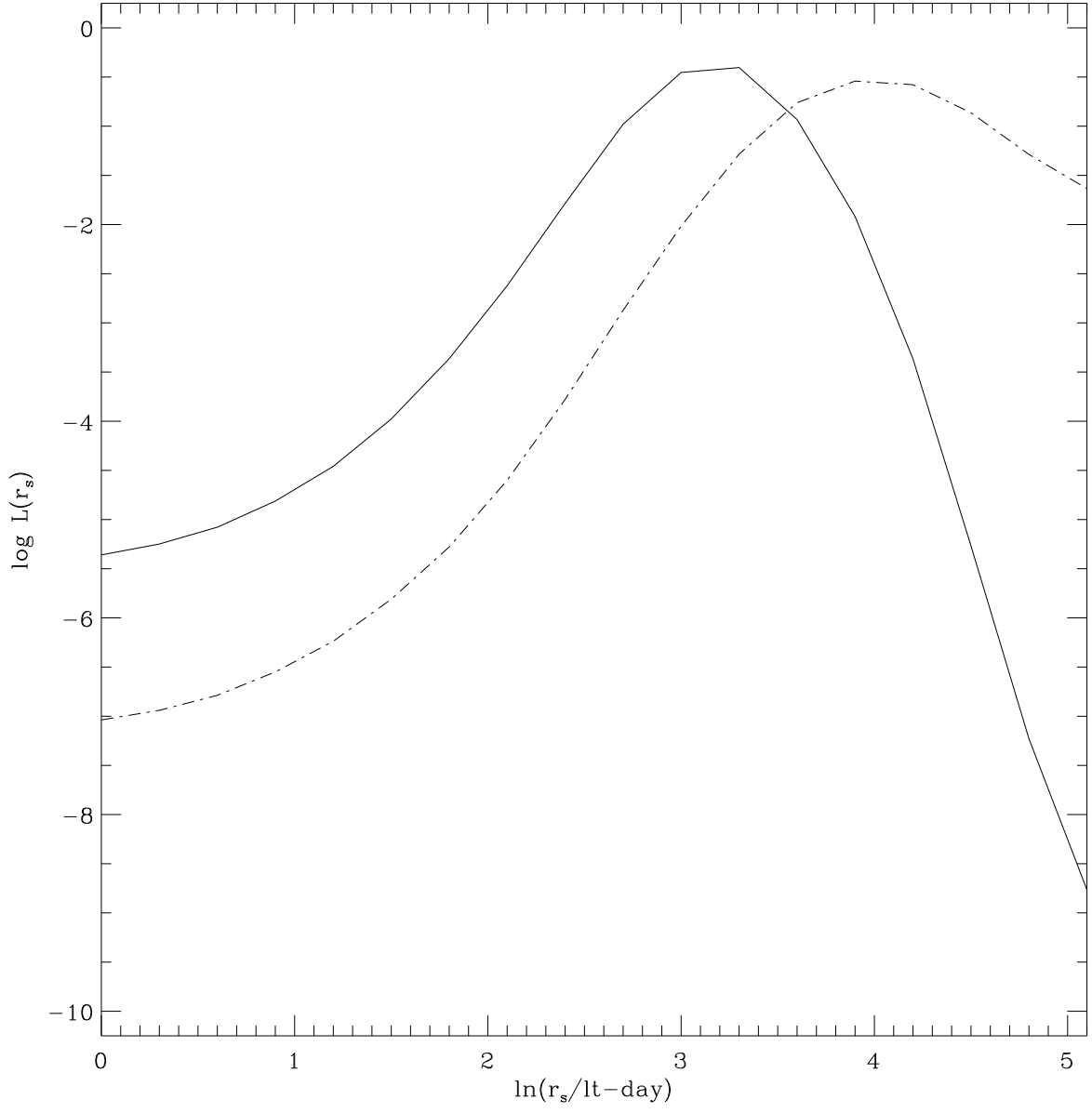


Fig. 5.— Maximum likelihood curves for the size of the regions of high (solid) and low (dashed) ionization lines, respectively.

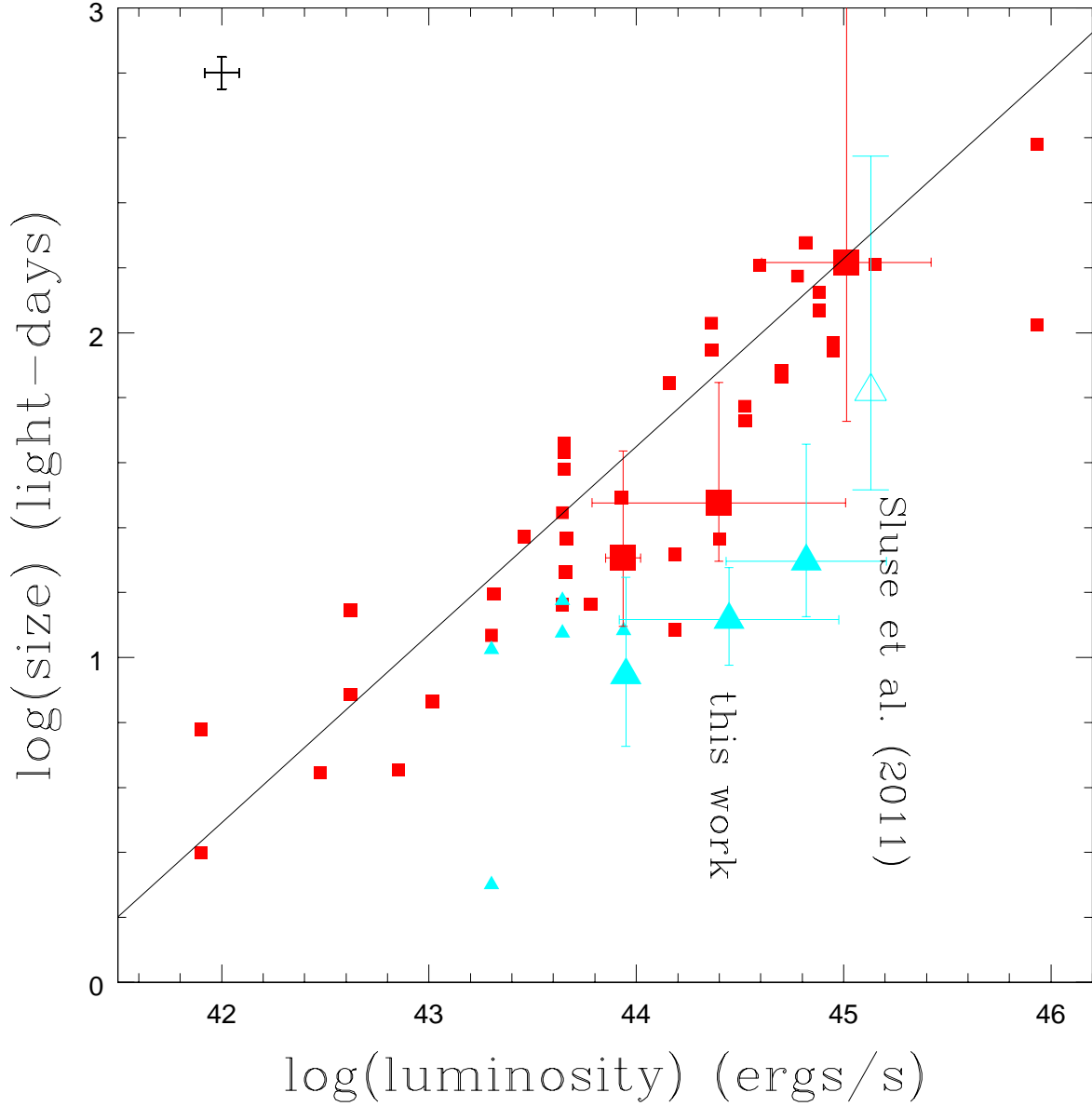


Fig. 6.— Estimates of high (red) and low (blue) ionization broad line region sizes as a function of quasar luminosity. The present results (large solid triangles and squares) and the result by Sluse et al. (2011) for Q2237+0305 (large open triangle) are shown using the magnification-corrected luminosity estimates of Mosquera & Kochanek (2011). The three large solid blue triangles (red squares) from the present work correspond to the low, total and high luminosity subsamples defined in our data for the high (low) ionization lines (see text). The results from local reverberation mapping studies are shown by the small triangles (high ionization lines) and squares (low ionization lines), using the uniform estimates of the lags by Zu et al. (2011) and the host-corrected luminosities from Bentz et al. (2009). The line is the best-fit correlation found by Zu et al. (2011). The cross in the upper left corner shows the average uncertainty of the reverberation mapping lag and the variance in the source luminosity during the mapping campaign.

Table 1: Differential microlensing, $\Delta m_{core} - \Delta m_{wings}$, of the high (HIL) and low (LIL) ionization emission lines

Object (pair)	$\lambda 1035$	$\lambda 1216$	$\lambda 1400$	$\lambda 1549$	$\langle \text{HIL} \rangle$	$\lambda 1909$	$\lambda 2798$	$\lambda 4861$	$\lambda 6562$	$\langle \text{LIL} \rangle$
HE 0047–1756 (B-A)	-	-	-	+0.03	+0.03	+0.03	-	-	-	+0.03
HE 0435–1223 (B-A)	-	-	-	-0.21	-0.21	-0.19	-	-	-	-0.19
HE 0435–1223 (D-C)	-	-	-	+0.19	+0.19	+0.07	-	-	-	+0.07
HE 0512–3329 (B-A)	-	+0.04	-	-	+0.04	-	-	-	-	-
SDSS 0806+2006 (B-A)	-	-	-	-	-	+0.09	-0.26	-	-	-0.10
SBS 0909+532 (B-A)	-0.43	-0.23	-	-0.04	-0.18	-0.01	-0.02	-0.14	+0.00	-0.04
SDSS J0924+0219 (B-A)	-	-	-	-	-	+0.09	+0.09	-	-	+0.09
FBQ 0951+2635 (B-A)	-	-	-	-	-	-	+0.04	-	-	+0.04
QSO 0957+561 (B-A)	-	+0.03	-	+0.03	+0.03	+0.08	-0.13	-	-	-0.03
SDSS J1001+5027 (B-A)	-	-	-	-0.04	-0.04	+0.01	+0.04	-	-	+0.02
SDSS J1004+4112 (B-A)	-	-0.07	-0.29	-0.23	-0.20	-0.06	+0.02	-	-	-0.02
QSO 1017–207 (B-A)	-	-0.08	-	+0.15	+0.03	-	-	-	-	-
HE 1104–1805 (B-A)	-	+0.03	-	+0.02	+0.02	+0.03	-	-	-	+0.03
PG 1115+080 (A2-A1)	-	-	-0.10	-0.04	-0.07	-	-	-	-	-
SDSS J1206+4332 (A-B)	-	-	-	+0.17	+0.17	-0.12	+0.15	-	-	+0.01
SDSS J1353+1138 (A-B)	-	-	-	-	-	-0.16	+0.05	-	-	-0.06
SBS 1520+530 (B-A)	-	-	+0.19	+0.16	+0.18	-	-	-	-	-
WFI J2033–4723 (B-C)	-	-	-	-0.05	-0.05	-0.18	-0.14	-	-	-0.16